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General performance evaluation charts and effectiveness correlations for the design of thermocline heat storage system

Zhao Ma, Ming-Jia Li, Wei-Wei Yang *, Ya-Ling He

Key Laboratory of Thermo-Fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

HIGHLIGHTS

- Three dimensionless design parameters are proposed for thermocline heat storage.
- Dispersion-concentric model is used to study effects of dimensionless parameters.
- General performance evaluation charts are proposed for performance evaluation.
- Effectiveness correlations are derived to design thermocline heat storage.

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ABSTRACT

One-tank molten salt thermocline heat storage system can reduce capital cost due to the use of cheap heat storage materials as compared with two-tank molten salt heat storage system. In order to develop a convenient method for the evaluation and design of the one-tank thermocline heat storage system, the idea of effectiveness-number of transfer unit method (ε-NTU) for heat exchanger design was employed in which three dimensionless design parameters are defined including the ratio between overall thermal conductance and the total thermal capacity of heat transfer fluid flowing through the system during discharging process (i.e., NTU), the ratio between thermal capacity of solid particles and total thermal capacity of heat transfer fluid through the system during the discharging process (i.e., C_s^*), the ratio between overall thermal conductance in the charging process and that in the discharging process (i.e., $(hA)^*$). A transient one-dimensional dispersion-concentric model is then applied to study the effects of three dimensionless parameters on the effectiveness of one-tank system. It is shown that the effectiveness of the one-tank thermocline heat storage system is closely related to NTU, C_s^* and $(hA)^*$. Based on the simulated results, general performance evaluation charts and the related effectiveness correlations are also proposed for evaluation and design of the one-tank system. Moreover, the proposed effectiveness correlations are finally applied in the design of a one-tank molten salt thermocline heat storage system in a 50 MW_e CSP plant.

1. Introduction

Solar energy has been regarded as a promising renewable energy source owing to the virtues of abundance, cleanness and easy accessibility, which has been applied in many ways such as solar buildings (Akeiber et al., 2016), solar water heating (Souliotis et al., 2016) and solar photovoltaic (PV) power generation and concentrated solar power (CSP) (He et al., 2011; Li and Chen et al., 2017). Compared with solar PV power station, the energy conversion efficiency of CSP system is higher. However, due to the time-dependent variation of solar radiation in a day and the instability of weather conditions, the heat storage systems (Ma and He et al., 2017) are usually required in CSP plants in order to maintain stable system operation and overcome the mismatch problem between the solar energy supply and the energy demand.

Currently, the two-tank molten salt heat storage system has been successfully applied in large-scale commercial CSP plants (He et al., 2016). Although the two-tank heat storage system is relatively easy to be operated, such a system usually requires large amount of expensive molten salt as heat storage material, which leads to the high capital cost of the whole system. As an alternative, the one-tank thermocline heat storage technology exhibits its potentiality and superiority. Unlike two-tank system, in one-tank thermocline heat storage system, the tank is actually filled with cheap solid fillers which stores sensible heat and the molten

* Corresponding author.
E-mail address: yangww@mail.xjtu.edu.cn (W.-W. Yang).

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Nomenclature

C	thermal capacity flow rate, $J \cdot s^{-1} \cdot K^{-1}$
c	specific heat, $J \cdot kg^{-1} \cdot K^{-1}$
H	height of storage tank, m
h	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
$\dot{m}$	mass flow rate of heat transfer fluid, $kg \cdot s^{-1}$
P	period, s
P_e	electricity power, W
T	temperature, K
t	time, s
u	velocity, $m \cdot s^{-1}$
V	volume, m^3

Greek symbols

ε	heat storage effectiveness
η_{th}	thermal efficiency
λ	thermal conductivity, $W \cdot m \cdot K^{-1}$
ρ	density, $kg \cdot m^{-1}$
φ	void fraction

Subscripts

act	actual thermocline heat storage system
c	cold
char	charging
dischar	discharging
eff	effective
h	hot
ideal	ideal thermocline heat storage system
in	inlet
l	liquid
out	outlet
p	pressure
R	outer radius of solid particle
r	radial coordinate inside each solid particle
s	solid particle

Abbreviations

CSP	concentrated solar power
HTF	heat transfer fluid
NTU	number of transfer unit

salt or thermal oil serves as heat transfer fluid (HTF) which flows through the tank. As a consequence, the capital cost of the whole heat storage system can be greatly reduced. Sandia National Laboratories (Pacheco et al., 2002) built the first pilot-scale molten salt thermocline heat storage system with thermal capacity of 2.3 MWh. In the system, silica sand and quartzite rock were used as solid filler. The studies showed that the thermocline heat storage system has lower capital cost than that in two-tank molten salt heat storage system. Besides, the studies by Electric Power Research Institute (Libby, 2010) also indicated that the capital cost of one-tank system can be reduced by 20–37% as compared with two-tank system. Although promising, however, there exists temperature gradient (i.e., the thermocline) in one-tank thermocline heat storage system and it consequently leads to the fact that the heat energy stored in the tank cannot be completely utilized which decreases the heat storage effectiveness of overall system. It is thus essential to investigate the performance of the one-tank thermocline heat storage system.

During the past decade, many experimental studies have been conducted on exploring the heat storage performance of one-tank thermocline heat storage system (Bruch et al., 2014; Flueckiger et al., 2011; Grirate et al., 2016; Yin et al., 2014). For example, Bruch et al. (2014) experimentally tested the performance of a pilot-scale oil/rock thermocline heat storage system. It was found that the efficiency of one-tank thermocline heat storage is sensitively influenced by the thickness of thermocline layer in the tank. Yin et al. (2014) experimentally investigated the performance of a molten salt thermocline heat storage system. In their system, zirconium ball and silicon carbide foam were used as heat storage fillers. It was shown that due to the existence of thermocline layer, the heat storage efficiency of this thermocline heat storage system is relatively lower than that of two-tank heat storage system. Zanganeh et al. (2015) also tested the performance of a high-temperature hybrid thermocline thermal energy storage system. In their system, the sensible and latent heat were combined in order to stabilize the air outlet temperature during the discharging process. The results showed that the outlet temperature of air can be maintained around 575 °C. Recently, PROMES-CNRS laboratory (Hoffmann et al., 2016, 2017) built a thermocline heat storage system with the heat capacity of 8.3 kWh. In the system, totally, 325 kg quartzite rocks were used as solid fillers for heat storage and the rapeseed oil was used as heat transfer fluid which can be heated up to 210 °C. A parametric study was then conducted related with the size of the particles and the inlet fluid velocity for this system and optimal fluid velocity was determined. It should be mentioned that the sizes of laboratory-scale experimental systems are usually quite small as compared with practical systems (Bayón and Rojas, 2013). As a result, the findings from the laboratory-scale studies may not be suitable for the design of industrial-scale thermocline heat storage system.

In tandem with experimental studies, some researchers also carried out numerical simulations to investigate the influences of main operation and structural parameters and to optimize the thermocline heat storage system (Flueckiger and Garimella, 2012; Wu et al., 2016; Xu et al., 2013; Yang and Garimella, 2013). Yang and Garimella (2013) employed a two-dimensional two-temperature model to study the cyclic behavior of thermocline heat storage system. The effects of tank height, the flow rate of molten salt and the size of solid fillers on the performance of thermocline heat storage system were analyzed. It was found that the particle diameter of filler and the volume of tank strongly influence the system efficiency. The system heat storage efficiency can be improved with smaller Reynolds number, larger length ratios (i.e., the ratio between flow distance of molten salt in half-cycle and the filler particle diameter) and larger tank height. Xu et al. (2013) also developed a transient, two-dimensional, two-phase dispersion-concentric (D-C) model for studying the packed-bed molten-salt thermocline heat storage system. The influences of solid particle properties including particle diameter and particle material on thermal performance of system were investigated. The results showed that increasing particle diameter can reduce heat transfer rate between solid particles and molten salt which finally can result in a decrease of the effective discharging time and discharging efficiency. Besides, Wu et al. (2016) also applied a transient, one-dimensional D-C model to study the cyclic behaviors of molten-salt packed-bed thermal energy storage system which is filled with cascaded phase change material capsules. In addition to above studies, there are relatively few studies on developing the convenient method for the design and calibration of thermocline heat storage system. For example, Li et al. (2011) proposed generalized charts of energy storage effectiveness for thermocline heat storage system design.